

The Black Hole Candidate LS I +61°303

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ABSTRACT

In recent years, fundamental relationships for the black hole X-ray binaries have been established between their X-ray luminosity L_X and the photon index Γ of their X-ray spectrum. For the moderate-luminosity regime, an anti-correlation between Γ and L_X has been observed. In this article, aimed to verify if the moderate luminous X-ray binary system LS I +61°303 is a black hole, we analyse *Swift* observations of LS I +61°303. We compare the derived L_X vs Γ distribution, first with the statistical trend for black hole X-ray binaries, then with the trend of the pulsar PSR B1259-63, and finally with the individual trends of the black hole X-ray binaries Swift J1357.2-0933 and V404 Cygni. We find that the system PSR B1259-63 shows a positive correlation between Γ and L_X , whereas in contrast LS I +61°303 shows the same anti-correlation as for black hole X-ray binaries. Moreover, the trend of LS I +61°303 in the $L_X/L_{\text{Eddington}} - \Gamma$ plane overlaps with that of the two black holes Swift J1357.2-0933 and V404 Cygni. All three systems, Swift J1357.2-0933, V404 Cygni and LS I +61°303 well trace the last part of the evolution of accreting black holes at moderate-luminosity until their drop to quiescence.

Key words: Radio continuum: stars - Stars: jets - Galaxies: jets - X-rays: binaries - X-rays: individual (LS I +61°303) - Gamma-rays: stars

1 INTRODUCTION

X-ray binaries are stellar systems formed by a normal stellar component and a compact object that could be a black hole or a neutron star (Lewin et al. 1997). The usual method for distinguishing the nature of the compact object is to determine its mass. In fact, Kalogera & Baym (1996) determined that the maximum gravitational mass of a neutron star for stability against gravitational collapse is $2.2 - 2.9 M_\odot$, with $2.9 M_\odot$ as the safest estimate. Therefore, a compact object with mass above $2.9 M_\odot$, is identified as black hole candidate (Kalogera & Baym 1996). The mass is determined by the mass function obtained by optical observations (Lewin et al. 1997):

$$f = \frac{M_X^3 \sin^3 i}{(M_X + M)^2} \quad (1)$$

where, M_X is the mass of the compact object, M is the mass of the companion star, and i is the inclination of the orbital plane. Another possible way to determine a black

hole in a X-ray system results directly from X-ray observations. Indeed, there is a clear relationship between the photon index Γ and the X-ray luminosity L_X for black hole X-ray binaries. The latest statistical study of black hole X-ray binaries (Yang et al. 2015,b) shows that over a luminosity interval covering more than three orders of magnitude, $\sim 10^{33} \leq L_X \leq 10^{36.5}$ erg/s, there is an anti-correlation between Γ and the 2-10 keV luminosity, L_X , in the form of $\Gamma = (-0.11 \pm 0.01) \log_{10} L_X + (5.63 \pm 0.017)$.

The system LS I +61°303 is one of the very few radio emitting X-ray binaries being associated with a source of very high energy gamma ray emission (Albert et al. 2006). In this X-ray binary, the compact object orbits around a Be star with an orbital period equal to 26.4960 ± 0.0028 d (Hutchings & Crampton 1981; Gregory 2002). As described in Sec. 2, the mass function does not allow a precise determination of the mass of the compact object in LS I +61°303, and consequently is still under debate if a neutron star or a black hole is the engine of this rare X-ray binary emitting all over the electromagnetic spectrum. In the present work, aimed to discriminate the nature of the compact object in LS I +61°303, we investigate if the X-ray charac-

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teristics of LS I +61°303 fit with those of black hole X-ray binaries. We present our analysis of *Swift* observations of LS I +61°303 (Sect. 3) and compare the derived L_X vs Γ distribution with the trend of the pulsar PSR B1259-63 and with the trend of the black holes (Sect. 4). Our conclusions are presented in Sect. 5.

2 THE MICROQUASAR AND PULSAR SCENARIOS

A small percentage of X-ray binaries, called microquasars, have radio emitting jets, probed either directly by high resolution radio images, or indirectly by their radio spectrum, that, for a steady jet is flat (Spencer 1996; Mirabel & Rodríguez 1999; Fender 2001). In a microquasar the radio jet is related to the behaviour of an accretion disk around a black hole, as in High Mass and Low Mass X-ray binary systems (HMXB, LMXB) or to an accretion disk around a neutron star with a low ($\leq 10^8$ G) magnetic field as in LMXB (Migliari & Fender 2006). Besides from accretion-powered radio jets, radio emission is observed also from X-ray systems, such as PSR B1259-63, having as compact object a fast rotating, non accreting neutron star with strong magnetic-field ($\sim 10^{12}$ G). In this case the observed continuum radio emission is due to particles accelerated at the shock between the relativistic wind of the pulsar and the wind of the companion star (Tavani et al. 1994; Moldón et al. 2012; Chernyakova et al. 2014).

The strong radio emitting HMXB LS I +61°303, proposed to host a black hole (Punsly 1999), shows resolved radio jets (Massi et al. 2012, and reference therein) and a flat radio spectrum (Zimmermann et al. 2015). In particular, the fact that the flattening of the spectrum occurs twice along the orbit suggests two main accretion events along the orbit (Massi & Kaufman Bernadó 2009; Jaron et al. 2016). Specifically, Kaufman Bernadó et al. (2002) suggested LS I +61°303 be a precessing microblazar. In this kind of microquasars, the precession brings the approaching jet component closer to the line of sight and the approaching jet component gets boosted. On the contrary, the receding jet component is de-boosted, an effect observed in LS I +61°303 with a sequence of VLBA images showing the change from a two-sided jet to an one-sided structure (Massi & Torricelli-Ciamponi 2014, fig. 7). In contrast to the microquasar scenario, the one-sided radio jet of LS I +61°303 was alternatively interpreted by Dhawan et al. (2006) as the cometary tail predicted by Dubus (2006) for the outflowing shocked wind material resulting from the interaction between a pulsar wind and the companion wind. The hypothesis of a strong magnetic field neutron star in LS I +61°303 was considered also by Torres et al. (2012) assuming an association of the system to a magnetar event detected in a crowded X-ray field with other potential candidates besides LS I +61°303 (Rea & Torres 2008).

Casares et al. (2005) used optical spectroscopy to measure a mass function $f = 0.0107 M_\odot$ of LS I +61°303. Optical polarization observations have determined a value of ~ 25 degrees for the rotational axis, r , of the Be disk in LS I +61°303 (Nagae et al. 2006). For parallel orbital and Be spin axes, i.e., $i = r$, and a mass of the B0 star $M = 17.5 M_\odot$ (Townsend et al. 2004), the mass of the compact object in

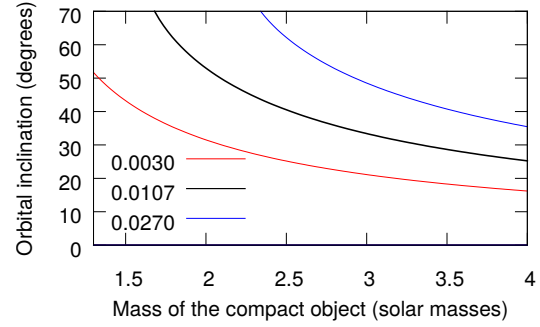


Figure 1. Mass of the compact object in LS I +61°303 as a function of the inclination angle, for three different values of the mass function (Casares et al. 2005) (see Sec. 2).

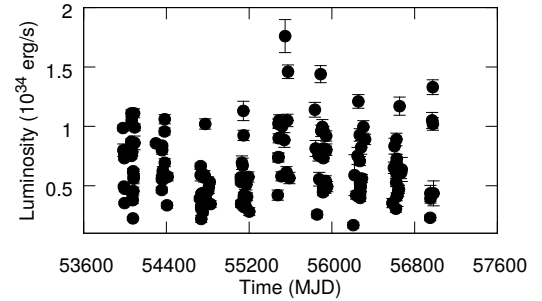


Figure 2. X-ray light curve (1-10 keV) of *Swift* LS I +61°303 observations.

LS I +61°303 is equal to $4 M_\odot$ (Fig. 1), clearly above the $2.9 M_\odot$ limit of Kalogera & Baym (1996) and therefore indicates a black hole. However, the range of uncertainty of the mass function is rather large, $0.003 - 0.027 M_\odot$ (Fig. 1), and in addition the i and r axes could be tilted. This means that optical observations only give a hint for the presence of a black hole in LS I +61°303. In the next sections we analyse if this hypothesis is corroborated or ruled out by X-ray observations.

3 DATA

We analyse *Swift*/XRT (1-10 keV) data in the interval 53980–56983 MJD using FTTOOLS/HEASOFT 6.14 tools. LS I +61°303 was observed both in Photon Counting (PC) and Windowed Timing (WT) modes. The initial cleaning of events is done using *xrtpipeline* with standard parameters (<http://www.swift.ac.uk/analysis/xrt/index.php>). For the source extraction region in the PC mode we use a circle with radii from 5 to 30 pixels depending on the count rate (Evans et al. 2009); for the WT mode the radius of the source extraction region is selected to be equal to 25 pixels. To collect the background we use an annulus region with an inner (outer) radius of 60 (110) pixels in both observational modes. The count rate from the source was too low to pile up the detector in any of the observations. Selection of data points with better than 3σ detection in both flux and photon index results in 150 *Swift* data points shown in Fig. 2.

We also take into account published historical data with the better than 3σ detection level: *XMM-Newton* data for

LS I +61°303 (Sidoli et al. 2006; Anderhub et al. 2009, re-computed at 1-10 keV); *Swift* and *XMM-Newton* data for the pulsar PSR B1259-63 (Chernyakova et al. 2006, 2009, 2014, 2015); *Swift* data for the black hole X-ray binary Swift J1357.2-0933 (Armas Padilla et al. 2013) and *Chandra* data for the black hole X-ray binary V404 Cygni (Plotkin et al. 2017). For the luminosity calculation we assume a 2.0 ± 0.2 kpc distance to LS I +61°303 (Frail & Hjellming 1991), 2.3 kpc distance to PSR B1259-63 (Negueruela et al. 2011), 2.29 kpc distance to Swift J1357.2-0933 (Mata Sánchez et al. 2015), 2.39 ± 0.14 kpc distance to V404 Cygni (Miller-Jones et al. 2009).

4 RESULTS AND DISCUSSION

In this section we present our results for LS I +61°303 and PSR B1259-63 and compare them with the results of Yang et al. (2015b) for a statistical sample of black hole X-ray binaries. We also compare here the behaviour of LS I +61°303 with that of the two moderate-luminosity black hole X-ray binaries V404 Cygni and Swift J1357.2-0933.

In the left panel of Fig. 3 *Swift* data (red circles) and *XMM-Newton* data (red squares) of LS I +61°303 in the $L_X - \Gamma$ plane are presented. The data cover the luminosity range $2.0 \times 10^{33} \leq L_X \leq 1.8 \times 10^{34}$ erg/sec. The data from the two different satellites (averaged over luminosity bins of 0.6×10^{33} erg/sec) are given separately to show the agreement of the two different data sets: points at the same luminosity result in the same photon index. The combined and averaged over luminosity bins of 0.6×10^{33} erg/sec data from both satellites, are given in Table 1. The fit of these averaged LS I +61°303 data results in:

$$\Gamma_{\text{LS I +61303}} = (-0.13 \pm 0.09) \log_{10} L_X + (6 \pm 3) \quad (2)$$

with reduced $\chi^2=1.2$. The fit is shown with a red line in the left panel of Fig. 3. We compare this fit of LS I +61°303 with that of the statistical sample of black hole X-ray binaries at moderate-luminosity, i.e., $\sim 10^{33} \leq L_X \leq 10^{36.5}$ erg/sec by Yang et al. (2015b):

$$\Gamma_{\text{Black Holes}} = (-0.11 \pm 0.01) \log_{10} L_X + (5.63 \pm 0.017) \quad (3)$$

Clearly the two independent fits determine the same slope of ~ -0.1 for LS I +61°303 and the statistical sample of black hole X-ray binaries. The black line drawn in the left panel of Fig. 3 corresponds to $\Gamma = -0.12 \log_{10} L_X + 5.63$. We perform now the same comparison for the non accreting pulsar PSR B1259-63. The right panel Fig. 3 show *Swift* data (blue circles) and *XMM-Newton* data (blue squares). Our least square fit for averaged PSR B1259-63 data results in:

$$\Gamma_{\text{PSR B1259-63}} = (+0.47 \pm 0.05) \log_{10} L_X - (15 \pm 2) \quad (4)$$

with reduced $\chi^2=19$. In Fig. 3 the fit for PSR B1259-63 is represented by a blue line. The slope, in this case is $+0.47 \pm 0.05$. That is in the considered luminosity range an increasing luminosity corresponds to an increasing photon index. This is clearly different from the anti-correlation between Γ and luminosity typical for black hole X-ray binaries in the same luminosity range. PSR B1259-63 data cover the luminosity range of $2.0 \times 10^{32} \leq L_X \leq 3.4 \times 10^{34}$ erg/sec This is a

Table 1. Photon index and luminosity of LS I +61°303 as observed by *Swift* and *XMM-Newton*. Data are combined and averaged over luminosity bins of 0.6×10^{33} erg/s.

Γ	$\Delta\Gamma$	L_X (10^{33} erg/s)	ΔL_X (10^{33} erg/s)
2.00	0.17	2.04	0.18
1.65	0.13	2.61	0.09
1.55	0.10	3.23	0.06
1.58	0.06	3.83	0.06
1.73	0.07	4.42	0.04
1.61	0.08	4.94	0.04
1.58	0.06	5.61	0.04
1.64	0.13	6.08	0.05
1.58	0.06	6.78	0.08
1.59	0.05	7.34	0.05
1.67	0.06	8.03	0.04
1.59	0.05	8.62	0.07
1.48	0.07	9.09	0.07
1.58	0.04	9.81	0.06
1.56	0.05	10.40	0.05
1.41	0.15	11.10	0.00
1.43	0.20	11.50	0.12
1.26	0.21	12.10	0.57
1.33	0.18	13.30	0.62
1.62	0.06	14.50	0.10
2.06	0.28	17.60	1.39

bit larger than that covered by LS I +61°303. Restricting the linear fit for PSR B1259-63 data within the same luminosity interval of LS I +61°303, i.e., $2.0 \times 10^{33} \leq L_X \leq 1.8 \times 10^{34}$ erg/sec, does not change the result for PSR B1259-63 of a positive correlation between luminosity and photon index, the fit in fact results in: $\Gamma = (+0.37 \pm 0.08) \log_{10} L_X - (11 \pm 3)$ with reduced $\chi^2=22$.

We compare in the top panel of Fig. 4 LS I +61°303 with the two black hole binaries Swift J1357.2-0933 and V404 Cygni. The mass of the black hole in V404 Cygni is of $9.0_{-0.6}^{+0.2} M_\odot$ (Plotkin et al. 2017, and references therein); the mass of the black hole in Swift J1357.2-0933 is $12.4 \pm 3.6 M_\odot$ (Casares 2016). From the optical observations of LS I +61°303 discussed in the introduction (Fig. 1) the mass of LS I +61°303 is determined to be about $4 M_\odot$. The comparison of black hole X-ray binaries with different masses is done (e.g., Yang et al. (2015)) scaling the luminosity by the Eddington Luminosity, $L_{\text{Eddington}} = 1.26 \times 10^{38} [M_X/M_\odot] \text{ erg/sec}$. In the bottom panel of Fig. 4 we show the three systems, LS I +61°303, V404 Cygni and Swift J1357.2-0933 in the $L_X/L_{\text{Eddington}} - \Gamma$ plane. Besides one point at $L_X/L_{\text{Eddington}} = 3.5 \times 10^{-5}$ where the photon index of LS I +61°303 deviates more than one sigma from the photon index value of Swift J1357.2-0933 at the same luminosity, all other LS I +61°303 data line up and overlap with Swift J1357.2-0933. At $L_X/L_{\text{Eddington}} = 0.9 \times 10^{-5}$, all three systems, LS I +61°303, Swift J1357.2-0933 and V404 Cygni, overlap. The overlap continues between V404 Cygni and LS I +61°303 and at the lowest luminosities, where the prediction (Plotkin et al. 2013; Yang et al. 2015b) for black hole binaries dropping in their quiescent state is a photon index $\Gamma \sim 2$, all three systems, LS I +61°303, Swift J1357.2-0933 and V404 Cygni converge on that value.

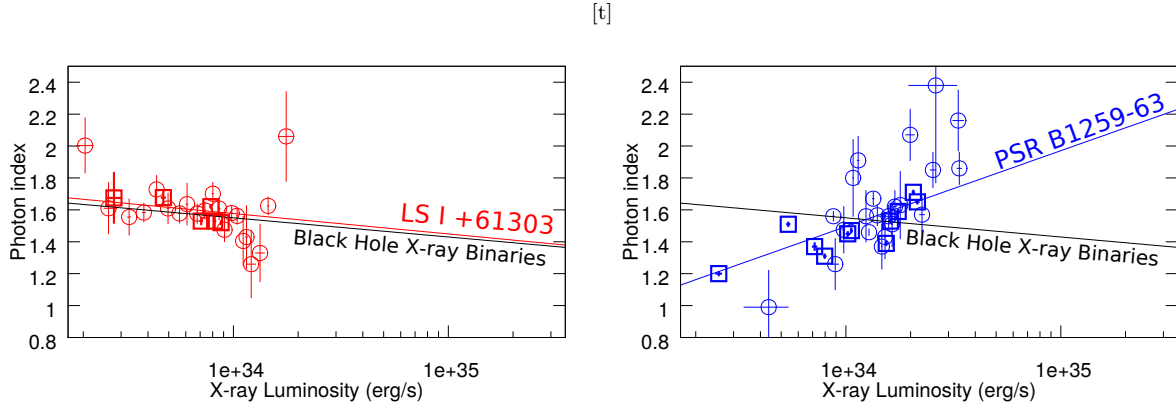


Figure 3. $L_X - \Gamma$ plane: LS I +61°303 (red) and PSR B1259-63 (blue) data with their fits. Circles indicate *Swift* data, and squares *XMM-Newton* data. The black line is the equation for black hole X-ray binaries $\Gamma = -0.12 L_X + 5.63$ (see Sect. 4).

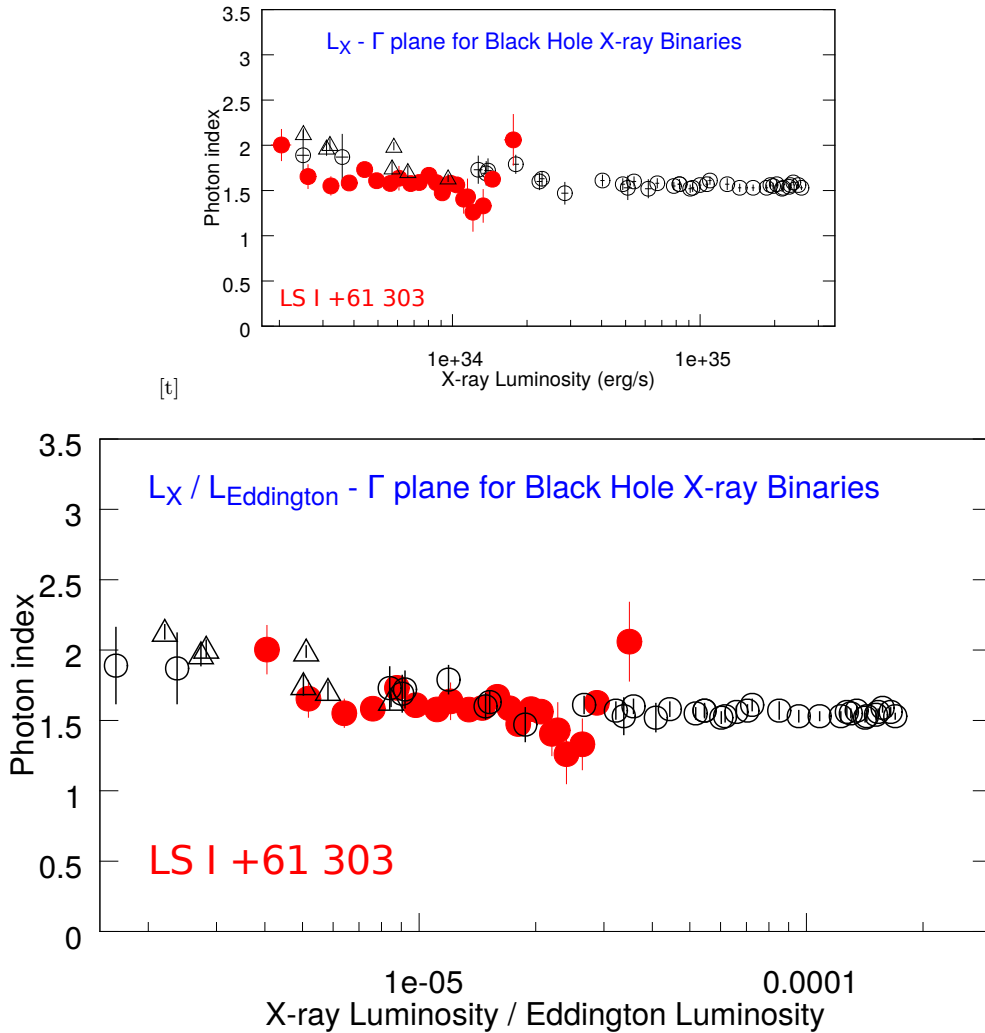


Figure 4. LS I +61°303 (red circles) and the black hole binaries V404 Cygni (black triangles) and Swift J1357.2-0933 (black circles) in the $L_X - \Gamma$ plane (top) and in the $L_X / L_{Eddington} - \Gamma$ plane (bottom). The LS I +61°303 data are those of Tab.1. The assumed masses are: $4M_\odot$ for LS I +61°303, $9M_\odot$ for V404 Cygni and $12 M_\odot$ for Swift J1357.2-0933 (see Sec.4).

5 SUMMARY AND CONCLUSIONS

High resolution images show a morphological change of the radio structure of the system LS I +61°303. Two scenarios have been proposed: the black hole - microquasar/microblazar scenario and the neutron star - pulsar/magnetar scenario. Optical observations indicate that the compact object in LS I +61°303 could be a black hole, but a neutron star cannot be excluded. In this work, as direct test of the black hole hypothesis we compare the X-ray characteristics of LS I +61°303 with those of black hole X-ray binaries in the same luminosity range. Our results are:

(i) the trend in the $L_X - \Gamma$ plane of LS I +61°303 is very different from that of the non-accreting pulsar PSR B1259-63. This result is at odds with the hypothesis (e.g., [Moldón et al. 2012b](#)) that the emission from the two systems could be due to the same physical process, i.e., the collision between a pulsar wind and the outflow of the companion star.

(ii) the trend of LS I +61°303 in the $L_X - \Gamma$ plane is in a good agreement with that of moderate-luminosity regime black holes in general and with Swift J1357.2-0933 and V404 Cygni in particular. This result corroborates the black hole - microquasar scenario for LS I +61°303 (e.g., [Massi 2004](#)) where the emission is due to the accretion-ejection physical processes.

These results point towards LS I +61°303 as the second known binary system where a black hole is orbiting a fast rotating B star, after the case of MWC 656 ([Casares et al. 2014](#)).

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